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HEAT TRANSFER IN THE TAUPO VOLCANIC ZONE (NZ): ROLE OF VOLCANISM AND HEATING BY PLASTIC DEFORMATION

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ABSTRACT

Natural heat transfer at the surface of the Taupo Volcanic Zone by intermittent volcanism and continuous discharge through high temperature geothermal systems is anomalously high (of the order of 5000 MW). The role of orogenic volcanism involving melts from the subducted lithosphere, heating of the crust by other melts from the lithosphere, and heating by plastic deformation of the lithosphere along a hinge line coinciding with the Taupo Volcanic Zone, is described. There is little evidence to support a back arc setting and an associated updoming of the asthenosphere, whereas the heat input by plastic shear deformation is significant. The combined heat input by orogenic volcanism and plastic deformation can explain the observed high heat output.

Introduction

World-wide mapping of high temperature geothermal systems during the last 25 years has shown that most of these systems have now been identified in countries with good reconnaissance surveys (GRC, 1985). These surveys indicate that the areal density of such systems differs between active margins as defined by plate tectonics. High temperature systems over active subduction zones associated with active calc-alkaline volcanism show different distribution patterns.

Along the South American subduction zone (Peru-Chile) and near the active margin of the Philippines there are less than three high temperature geothermal systems for an average, 100 km-long strip of undefined width striking parallel to the subduction zone. In Japan and Java the occurrence increases to about 4-5 systems per 100 km; however, in the Taupo Volcanic Zone (TVZ) in New Zealand, one finds about 10 systems per 100 km. The observed natural heat loss for the TVZ systems appears to lie within the median range of 100-300 MW (16 systems), whereas that of similar high temperature systems in Java and the Philippines lies within 50-200 MW (total of 15 systems studied). Assuming a random distribution of natural losses for a group of these systems, the figures indicate that heat transfer of the TVZ systems is anomalously high.

Since over long periods heat is not only transferred to the surface by thermal systems but also intermittently by volcanic eruptions, one has also to consider the volcanic heat transfer. It can be related to the mass of volcanic rocks deposited at the surface over a given period (say, the last 106 yr). These records are still incomplete, but it appears that the production rate of volcanic rocks in the TVZ is also rather high in comparison to that of volcanic centres with a high production of melts (Wilson et al., 1984).

For this'paper, it is inferred that the heat output of the TVZ is anomalously high in comparison to that of other active margins with a similar plate tectonic setting; the anomalous high heat output implies an anomalously high heat input into the crust. The question arises: what models can explain this?

Heat output of the TVZ

The anomalous heat output of the TVZ can be assessed by allowing both for intermittent heat transfer of molten rocks and continuous heat transfer by geothermal systems. The TVZ, as outlined by short wavelength magnetic anomalies associated with a sequence of extrusions and intrusions (Hochstein and Nathan, 1977), stretches from Mt Ruapehu in the S to White Island in the N and covers an area of about 8 x 10^3 km^2. Allowing for pyroclastic flows from the TVZ deposits outside and for airfall deposits, the total mass of volcanic rocks produced by the TVZ is probably of the order of 45 x 10^{15} kg, of which about 30 x 10^{15} kg was deposited during the last 106 yr. Assuming appropriate thermal constants, it can be inferred that about 3 E 19 kJ were transferred by volcanic rocks during the last 10^6 yr, equivalent to an energy rate of the order of 1000 MW.

Heat discharged by all high temperature systems in the TVZ is probably about 4000 MW, if one allows for the possibility that previously published data might contain a systematic error related to overestimates of steam losses (Hochstein, 1988). Assuming that heat transfer by geothermal systems has not changed much during the last 10^6 years, the estimate indicates that geothermal systems in the TVZ transfer about 4 times more heat than all other volcanic centres. In terms of equivalent heat transfer per unit area, a value of the order of 600 mW/m^2 is indicated. These values are similar to those listed by Hedenquist (1986).

Volcanic rocks deposited in the TVZ consist basically of three types: rhyolites and pyroclastic flows which make up at least 80% (by volume) of all volcanic rocks; andesites and dacites - probably about 10-20%; and rare (<0.1%) basalts. Our estimates for andesites differ from those previously cited (Wilson et al., 1984) but allow for the widespread occurrence of large wavelength magnetic anomalies in the TVZ, which for a few localities could be correlated with flank deposits of concealed large andesite extrusions (van Dijck, 1988).

In the following, simple conceptual models are discussed which can produce fusion of crustal and subcrustal rocks; it will be assumed that a significant portion of rhyolitic deposits in the TVZ are produced by crustal melts. As for other rhyolites, andesitic and dacitic rocks, it is assumed that these are mainly products of fusion of the top of the subducted plate (constrained to rocks containing hydrated minerals). With the exception of the assumption that most pyroclastic deposits in the TVZ are produced by crustal melts (Ewart and Stipp, 1968), the sequence follows the calc-alkaline differentiation trend of orogenic volcanism. The minor basalts are inferred to represent melts from the non-subducted lithosphere or the asthenosphere.

The problems with heat sou Is for the TVZ

Different models have been proposed to explain certain aspects of the anomalous heat transfer in the TVZ. Because of the limited space, no adequate references are given in the following; only key arguments are discussed.

If one only considers the heat source problem for geothermal systems, a simple hot plate of uniform high temperature at some upper crustal depth of, say, 5 km is sufficient; some continuous heating of this plate from below is also required. The model has no volcanic or tectonic implications. If continuous heating of the hot plate model were by conduction, it becomes invalid since the equivalent heat transfer, of 600 mW/m^2 would imply uniform melting point temperatures (i.e. >1000°C) below 5 km depth.

One can postulate intruding melts to produce both the heat for crustal melts discharged by volcanic centres and geothermal systems which would involve a series of randomly distributed cooling plutons in the crust. It reduces the problem of uniform crustal melts implied by the hot plate, but raises other problems. There is, for example, no evidence supporting the widespread Occurrence of cooling plutons beneath the TVZ; in addition, their size would have to be unusually large (>300 km^3) to maintain the heat output of most of the larger geothermal systems which are probably older than 0.1 M yr; the same applies to volcanic centres with a history of catastrophic eruptions lasting for even longer periods.

If one retains the concept of heat transfer involving molten rocks in the lower crust of the TVZ, the question arises as to the origin of these melts. If these melts originate from fusion of the subducted lithosphere, as indicated by the prevalence of calc-alkaline volcanism at the surface, these melts can only heat the lower crust by intrusions; (melts discharged at the surface do not contribute to crustal heating). Massive intrusions of the lower crust are doubtful for reasons stated above, although some pre-heating of the crust by orogenic volcanism cannot be discarded. Melts, however, can also originate from the lithosphere and the asthenosphere as well. In the case of large buoyancy forces associated with an upwelling asthenosphere, for example, it is likely that **these** melts would be accompanied by tholeiitic differentiation products. Minor basalts occur in the TVZ although without differentiation trends. One can explain this by assuming that such melts come from the upper lithosphere (not subducted plate), where buoyancy forces are small, thus leading only sporadically to extrusion. The conceptual model of widespread occurrence of basaltic melts near the top of the lithosphere can explain the high heat input into the crust of the TVZ (as originally proposed by Calhaem, cited in Stem, 1986), but it fails to explain the causes of the anomalous heating which produces melting. Nevertheless, the model has found wide acceptance and is used at present by many authors to explain the phenomenon of crustal melting in the TVZ

However, the model of basaltic melts beneath the bottom of the crust in the TVZ raises problems discussed previously in connection with the "hot plate" model within the upper crust, except that a problematic model has been pushed from a level of, say, 5 km depth to a level of, say, 40 km depth. One has to note, however, that sporadic melting of the lithosphere beneath the TVZ probably occurs, but is does not appear to be widespread although, again, it may contribute locally to some heating of the crust. There is no seismological evidence to support widespread melting within the crust ("crustal hot plate") and within the lithosphere ("basaltic hot plate").

So far, the role of plate tectonics and tectonic deformation has been neglected in the discussion. Deformation and paleomagnetic studies show that the TVZ is also a tectonically anomalous area. Probably it constitutes the hinge line between two plate segments of which one segment, given by the NE part of the N Island, rotates clockwise (about 6° during the last 10^6 yr) with respect to the NW segment. The hinge line is not only confined to the TVZ but curves to the SW towards Mt Egmont. Tensile stresses as well as shear deformation are dominant in the brittle crust beneath the TVZ, causing some separation and stretching of the heated crust which is supported by seismic data. Stretching of a crust sets in motion some secular updoming of the asthenosphere as it has been observed or inferred for other continental rifts and back arc basins within plates with an oceanic type of crust.

Secular updoming and convection of the asthenosphere, however, is a long and delayed process (Vanpé, 1984); in view of the young age of the TVZ it is doubtful whether the process, if induced by stretching of the crust, has even started yet since updoming would begin at depths below 200 km. The upper mantle has moved upwards beneath the TVZ, but such an uplift (of the order of 15 km) is not sufficient for rocks to reach pressure-melting point temperature at the top of the lithosphere, whatever temperature model for active margins one might use.

The presently-held theory that anomalous heating of the crust beneath the TVZ is provided by the heat input of massive melts beneath the crust-upper mantle boundary rests not so much on the few data which might support the model (or contradict other models) but on the assumption that the TVZ is pan of a back arc spreading centre. Following the original proposal by Karig (1970), most authors discussing the volcanism of the TVZ have adopted this assumption. The argument that the proposed back arc spreading centre coincides with an andesitic volcanic arc (Hatherton and Dickinson, 1969) has been neglected. The geometry argument, however, is important. Other oceanic back arc systems usually occur further away (100-200 km) from the median arc line with active calc-alkaline volcanism; these back arc depressions have wavelengths of the order of 100-200 km, compatible with the wavelength of the convection cell. The axis of the TVZ, however, coincides with the median arc line, and the TVZ depression has a wavelength of a few tens of kilometres.

The assumption of a back arc setting for the TVZ appears to be rather weak; if one discards this assumption, there is not much left to explain any melting beneath the bottom of the crust, and the associated high heat input into the crust.

One has to look, therefore, at other models, assuming that there is probably a connection between the phenomena of anomalous high heat transfer and anomalous tectonic deformation. Any conceptual model that can link the two phenomena would be an alternative model.

Important features which have to be explained by such a model are:

(1) Rifting of the TVZ and stretching of the hot crust.

(2) The magnitude of overall heat input into the crust has to be of similar order as the observed heat output.

(3) The model should allow for non-uniform heat input into the brittle crust leading to sporadic melting of crustal rocks beneath a few volcanic centres, but elsewhere the heat input should be lower so that melting point temperatures are not reached.

(4) Heat input into the upper lithosphere should also occur to produce local but not uniform melting near the top of the upper mantle.

(5) *Some* heat input into the lower lithosphere has to occur which might lead to fusion and volcanism outside the TVZ (i.e. beneath Mt Egmont).

Finally, the model should allow for some pre-heating of the crust by orogenic volcanism, i.e. ascending melts from the subducted lithosphere, but it should be decoupled. One can construct such a model by investigating the role of heat generated by plastic deformation, which is discussed below.

Heat input by plastic shear deformation

The concept of shear heating of the top of a subducted lithosphere plate has already been used to explain the generation of deeper melts associated with orogenic volcanism (Spohn, 1980). A similar concept can also be used to investigate the hypothesis whether rotational movement of a plate segment of the North Island can produce significant heat by plastic deformation. Theories describing plastic deformation show that all mechanical work can be transferred into heat once the applied force exceeds a limit F_{lim}, which can be calculated from material and geometrical constants. For simple bodies, the shear stress field can be described by the slip line field theory.

One can use the analogy of a bending cantilever to simulate the apparent clockwise rotation of the E part of the N Island of New Zealand (Walcott, 1988), where the TVZ represents the hinge line (Fig. 1). If a cantilever is loaded beyond the elastic limits, plastic deformation occurs which can be described by two field radii r and R related to the limit load and the geometry of the cantilever (see Fig. 2); the cantilever length is L, its thickness 2H and width is T. If the cantilever analogy is applied to the N Island plate rotation, L and 2H are the horizontal field dimensions and T its thickness (see Fig. 1).

Slip line field theory shows (Green, 1954 a,b) that the geometry of the deformation field is defined by:

$$r \sin(\pi/4 + \delta) + R \sin\beta = H \qquad (1)$$

where : $\beta = \pi/8 + 1/4$; $\delta = \pi/8 - 1/4$.

Forces acting on the plastic hinge line can be related to the limit load F_{lim} since, for unit thickness:

$$F_{lim} = 2k\,(H - r\,(1 + 2\delta)\sin\beta - 2R\,(\sin\beta - \beta\cos\beta)). \qquad (2)$$

The condition of dynamic equilibrium of forces and moments implies:

$$0.25\,R^2 + (0.41\,L - 0.31\,H)R + 0.04\,HL - 1.03\,H^2 = 0. \qquad (3)$$

The slip line field solution for plastic deformation at the hinge line of a cantilever is specified by the parameters L and 2H. Other parameters, like yield stress k, the thickness of the plate T and the rotation *a* are required to assess the work dissipated along the plastic hinge line. For the rotated plate segment (i.e. E part of N Island lying between the TVZ and the trench) we used the dimensions:

$L = 650 \pm 100$ km; $2H = 500 \pm 100$ km; $T = 120 \pm 50$ km.

The width of the shear zone (i.e. TVZ) was taken as $\Delta x = 25 \pm 10$ km (Hochstein and Nathan, 1977), for the yield stress we used 1 ± 0.3 kbar (Bird, 1988) and for the rotation *a* a value of $6° \pm 2°$ (Walcott, 1989) accumulated during the last 10^6 years.

Applying these values to equations (3) and (1) gives

R = 230 km (i.e. distance to pole of rotation),

r = 140 km (i.e. radius to stress singularity).

Equation (2) applies to plane strain conditions and is expressed in terms of force per unit thickness (i.e. here in km) using the values for R and r listed above and allowing for the actual thickness of the plate T, one obtains:

$$F_{lim} = 25 \text{ Mbar km}^2 = 2.5\text{ E }18 \text{ N}.$$

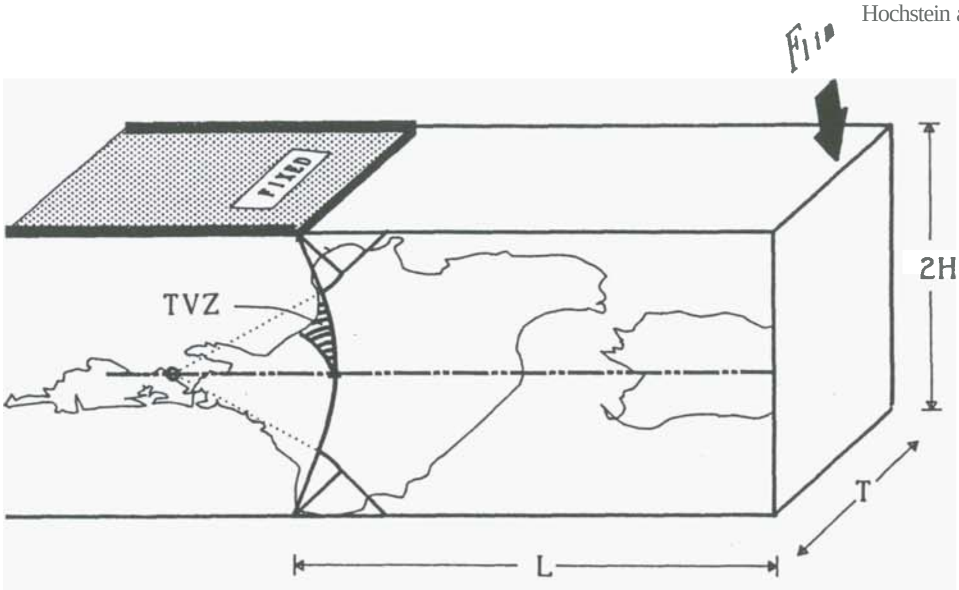


Fig. 1: Analogy of rotation of NE part of the N Island in terms of bending of a cantilever (the curved line indicates the hinge line).

The plastic deformation work W as a result of the rotation of $\alpha = 6°$ in the past 10^6 yr is then:

$$W = F_{lim} (L + u)\, \alpha, \quad \text{where } u = (R \cos\beta - r \sin\beta); \ \alpha \text{ in rads.}$$

This gives for the work dissipated along the hinge line during the last 10^6 yr a value of W = 1.9 E 20 kJ.

This work is dissipated as heat, slip lines therefore become "heat source lines". For the analogy used here it has been assumed that shear deformation is localized along the plastic hinge line. No plastic work is dissipated within the isosceles triangle in Fig. 2 because these move together with the rotating part of the plate as a rigid body. Plastic deformation only occurs below the brittle crust, its thickness is probably about 10 km beneath the TVZ. If one assumes that the plastic hinge line has a width given by the width of the shear zone within the TVZ, heat would then be dissipated over the areal extent of this shear zone. Assuming that all plastii deformation work is dissipated as heat, the heat generation per unit time then is:

$$Q = W/t \approx 6000 \text{ MW}.$$

This is only an order of magnitude estimate; a sensitivity analysis of all parameters used in assessing Q shows that the largest error is introduced by uncertainties in the accumulated rotation α, and the value of the shear stress k.

Implications of heat n

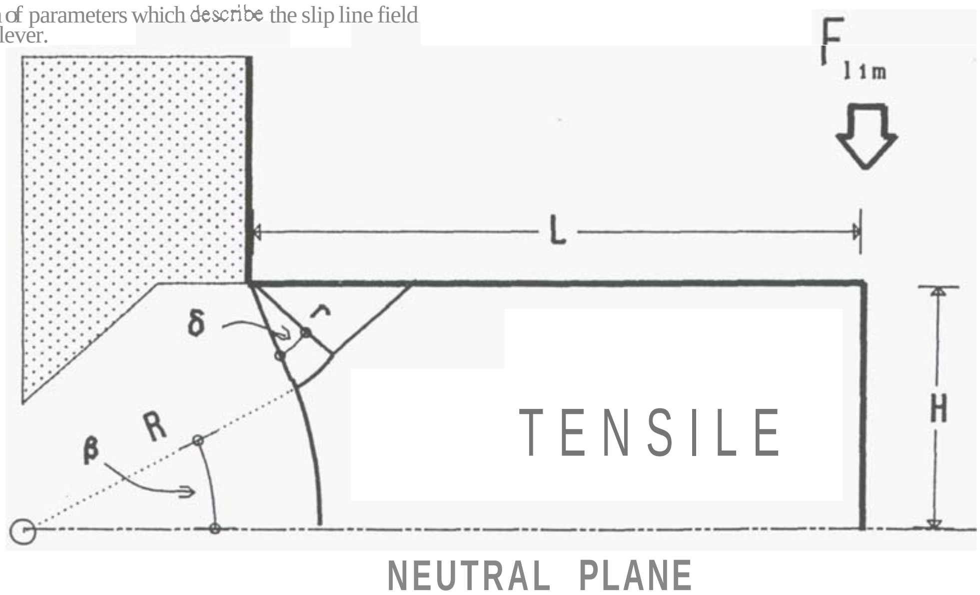
This simple model of generating heat within the lithosphere and lower *crust* beneath the hinge line can explain some important geological and geophysical features, namely:

(a) Tensile stresses are dominant in the N half of the rotated plate segment along the hinge line NE of Mt Ruapehu; rifting and wedge-shaped opening of the TVZ are a result of the rotation (i.e. no back arc setting is required to explain rifting of the TVZ). Tensile stresses in the brittle upper crust allow tensile fracturing, facilitating the ascent of melts from the subducted lithosphere but also ascent of crustal melts.

(b) The heat produced by plastic deformation along the hinge line is significant and of the right order of magnitude; it could produce high temperatures beneath the brittle *crust.*

(c) The model explains minor bunching of crustal earthquakes beneath the TVZ (Smith and Webb, 1986) as well as clustering of similar events along the hinge line which curves to the SW and W between Mt Ruapehu and Mt Egmont/Taranaki.

Fig. 2 Definition of parameters which describe the slip line field of a bending cantilever.



Although heat generation by plastic deformation is significant, it depends on the geometry of the slip line field which, in turn, depends on the shape of the rotated plate segment. A rectangular plate as used here is a poor fit of the real plate segment; the rotation is also constrained by contacts with other plate segments and this needs further work. Slip line field solutions for bending of plate segments with different geometry and for oblique loading exist (Ranshi et al., 1974); these solutions, if applied to the TVZ, indicate that heat production increases if one uses a plate segment which approximates the shape of tapered cantilevers. The magnitude of heat generated by plastic deformation therefore poses no problem. The simple plain strain model presented here is only an example which shows that significant heat can be generated even by using a very simple model.

With reference to points (3) and (4) describing the features of a suitable model listed previously and which require non-uniform heat input, the rotated rectangular plate model only produces uniform heating with depth. However, the resistance of crustal and subcrustal rocks against shear deformation is not uniform with depth. The strength of these rocks decreases rapidly beneath the brittle crust and again beneath the top of the upper mantle (Meissner and Strehlau, 1982). Introduction of non-uniform strength for crustal and sub crustal rocks will lead to an enhanced plastic deformation and, hence, non-uniform heating. Additional non-uniform heating in lateral direction is possible if the width of the shear zone varies laterally. In principle, it appears to be possible to produce non-uniform heating within the lithosphere beneath the TVZ both in lateral and vertical direction. Further studies are required to find out whether such non-uniform heating over realistic geological periods can raise temperatures up to the pressure-melting point.

There are also other features indicated by the model which are not supported by observational data, namely,

(d) There is little evidence for crustal heat being transferred along the SW part of the hinge line, i.e. there are no geothermal systems beneath Taranaki.

(e) Paleomagnetic data (Walcott, 1988) do not support significant rotation for the SW half of the rotated plate.

(f) If the heat input by plastic deformation would affect the whole lithosphere, it is more likely that this heating would produce melts in the lower part of the lithosphere where temperatures are closer to the pressure-melting point.

These arguments, however, are not too severe. Some heat generation in the deeper lithosphere beneath the SW extension of the hinge line could explain the volcanism of Mt Egmont. Because of the dominant compressive stresses along this curved extension of the hinge line, ascent of melts is restricted. As for the lack of evidence for rotation of the SW half of the plate segment, one could argue that the main structural units still follow the bending of the Stokes Magnetic Anomaly in that area (see Fig. 3). The low heat input into the crust beneath the Taranaki segment of the hinge line could be explained if one makes allowance for transient effects. Heat transfer from the plastically deformed rocks into the brittle crust involves conductive heat transfer. If the thickness of the brittle layer were greater beneath Taranaki than that beneath the TVZ, or if plastic deformation involved a wider zone and occurred at greater depths, the upward-travelling thermal front would be delayed and reduced beneath Taranaki. The problem whether significant melting can be produced in the deeper lithosphere can only be discussed when models for plastic deformation of a lithosphere with non-uniform strength have been investigated.

Summary

Present-day natural heat transfer and tectonic deformation in the Taupo Volcanic Zone appear to be anomalous if compared with similar features over active subduction zones in other parts of the world. A number of conceptual models have been suggested to explain the anomalous heating of the crust beneath the TVZ. Although most models assume that some heat transfer by molten rocks is involved at probably two levels, namely below the brittle crust (crustal melting) and somewhere near the top of the upper mantle, linkage between the phenomenon of melting and mechanisms which provide heat to cause melting is poor. The hypothesis that updomed hot asthenosphere material provides such a link depends mainly on the assumption whether the TVZ can be explained in terms of a back arc setting. One can raise arguments based on the geometry of asthenosphere convection cells and the location of back arc depressions with respect to the volcanic arc which refute this hypothesis.

The hypothesis cannot be discarded that the crust beneath the TVZ is heated by ascending and intruding melts which originate from the top of the subducted lithosphere (say at 100-150 km); however, there is no evidence which supports the occurrence of a large number of cooling plutons of large volume within the crust. It is also unlikely that these melts if stored in deeper magma chambers, cause fusion of rocks near the top of the upper mantle since minor basalts, which probably come from the upper mantle, are unmixed.

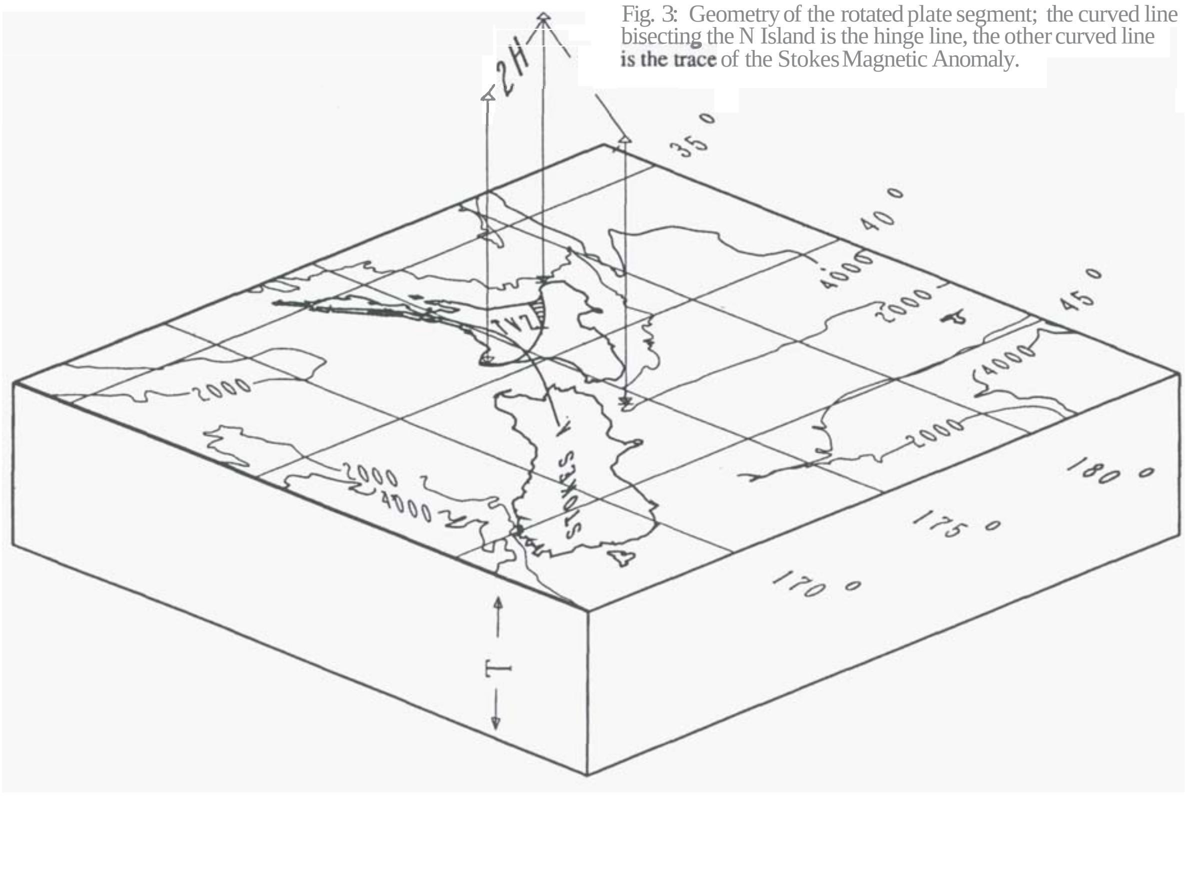


Fig. 3: Geometry of the rotated plate segment; the curved line bisecting the N Island is the hinge line, the other curved line is the trace of the Stokes Magnetic Anomaly.

A conceptual model which involves heat generation by localised plastic deformation can overcome many of the problems. The special tectonic setting of the TVZ, which constitutes a hinge line for the secular rotation of the NE part of the North Island, can be used to investigate heat generation within the lithosphere by plastic deformation. Using the analogy of a bending cantilever and describing the plastic deformation at the hinge line with slip field line theory, it was found that significant heat can be generated beneath the brittle crust. The heat generated depends on model characteristics, some other models can produce more heat. Uniform strength has been assumed for the whole lithosphere; non-uniform heat generation, i.e. non-uniform plastic deformation, is required to model enhanced heat generation at various levels of the lithosphere. A significant advantage of the model is that it links tectonic forces and anomalous heat transfer in the Taupo Volcanic Zone.

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